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ABSTRACT.

A simple, single channel 2mm microwave interferometer has been developed for plasma electron density measurements on the Joint European Torus experiment. A long (76m) plasma probing beam path in oversized waveguide enables all sensitive components to be located outside JET's biological shield. A high sensitivity liquid helium cooled InSb detector compensates for the high waveguide attenuation (~65dB). The maximum measurable electron density is expected to be limited by refraction to $\sim 8\times10^{19}$ electrons/m^3 ~250 fringes in the interferometer). Detection noise limits the minimum resolvable density change to $\sim\pm 1.6\times10^{16}$ e/m^3 ($\pm$ 20 millifringe). The system operates routinely and the maximum JET plasma density to date of $\sim 3\times10^{19}$ e/m ^{3} has been measured without difficulty.

In addition plasma density fluctuations which represent a variation of only 0.1% of the maximum density signal can be studied with the interferometer.

Introduction

JET is a large controlled fusion research tokamak with a major radius, R, of 2.96 m and a non-circular cross-section with minor radii a = 1.25 m, (horizontal) b = 2.13 m (vertical) [1]. The simple 2 mm microwave interferometer described here has been used as the primary density monitor throughout the ohmic heating phase of the JET programme. It measures the line integrated electron density along a single vertical plasma chord located at R = 3.14 m.

Access to the JET experimental device is restricted during an experimental period and all the active components of the interferometer are positioned outside the biological shield. This results in an unusually long total transmission path length of some 76 m for the plasma probing beam of the interferometer. More than 70 m of this transmission path is in oversized waveguide with a total of 24 low loss mitre bends. The total measured attenuation is 65 ± 3 dB. A 150 mW, 140 GHz reflex klystron is used as the microwave source and a high sensitivity liquid helium cooled InSb detector is used to compensate for the high attenuation. The maximum density achieved on JET to date caused a maximum phase excursion of ~ 100 fringes in the interferometer. This was recorded without difficulty by the instrument with the normal phase resolution of ± 20 millifringes. The high density resolution achieved makes the system a powerful diagnostic for the study of MHD oscillations in addition to its basic density monitoring role.

The details of the interferometer, examples of the basic JET density records and the detailed MHD phenomena detectable on these records are presented in this paper.

Principles and Limitations of the Measurement

The interferometer measures the change in path length between the plasma and reference beams caused by the change in refractive index of the plasma as its electron density grows and then decays during the JET Pulse.

The refractive index for a plasma is given by [2]

$$\mu = \left[1 - \left(\frac{f_{pe}}{f}\right)^2\right]^{1/2} \qquad (1)$$

where f is the probing beam frequency and f_{pe} is the electron plasma frequency,

$$f_{pe} = \left(\frac{e^2 \; n_e\,(r)}{4\pi^2\,\epsilon_o\,m_e}\right)^{1/2} = 8.97\,\left[n_e(r)\right]^{1/2} \qquad \text{MKS (2)}$$

e is the electronic charge,
$n_e(r)$ is the local electron density,
ϵ_o is the permittivity of free space and
m_e is the electron mass.

From equation (1) it is clear that for a particular probing frequency there exists a critical density, n_c, above which the probing beam will not propagate through the plasma. From equation (2) $n_c = f^2/80.4$ and equation (1) can then be re-written.

$$\mu = \left[1 - \frac{n_e(r)}{n_c}\right]^{1/2} \qquad (3)$$

The phase difference, $\Delta\phi$, produced by the plasma between the plasma and reference beams of the interferometer will then be

$$\Delta\phi = \frac{2\pi f}{c}\int_o^L (\mu - 1)\,dL \text{ radians} \qquad (4)$$

where c is the velocity of light and L is the total beam path length through the plasma.

To simplify Equation (3) the binomial expansion of μ to first order is used

$$\mu \simeq 1 - \tfrac{1}{2}\,.\left(\frac{n_e(r)}{n_c}\right)$$

then

$$\Delta\phi \approx \frac{80.4\cdot\pi}{cf}\int_o^L n_e(r)\,dL = \frac{80.4\cdot\pi}{cf}\;\bar{n}_e\cdot L \qquad (5)$$

where $\bar{n}_e$ represents density averaged over the beam path through the plasma.

For the JET 140 GHz probing beam the critical density is $2.43.10^{20}$ e/m^3. However, before this density limit is reached the approximation used in Equation (5) will become less valid. For example, for cases in which the density profile is flat and with $\frac{\bar{n}_e}{n_c} \simeq$ ¼ and ½, the approximation will lead to a systematic over estimate of $\bar{n}_e$ by 1%, and 6% respectively.

Although the beam is not cut off at these densities it may be refracted away from the receiving antenna if the plasma is not well centred on the vertical probing path.

The effects of refraction have been computed by a number of authors [3,4]. For a parabolic density distribution on JET an approximate limit has been estimated by setting the maximum acceptable beam refraction angle equal to the beam divergence angle of the launching antenna. This leads to the requirement that for

$$\frac{n_e(o)}{n_c} = \tfrac{1}{2}$$

where $n_e(o)$ is the central density, the plasma should be centred within ~ 10 cm of the probing beam path. This is normally the case and thus indicates that the 140 GHz interferometer should be usable up to a mean density of about 8.10^{19}/m^3. The maximum average density achieved on JET to date is ~3.10^{19} e/m^3 which created 100 fringes in the interferometer and was measured without difficulty.

The minimum resolvable phase change is limited to about ± 20 millifringes by digital and detection system noise which are about equal.

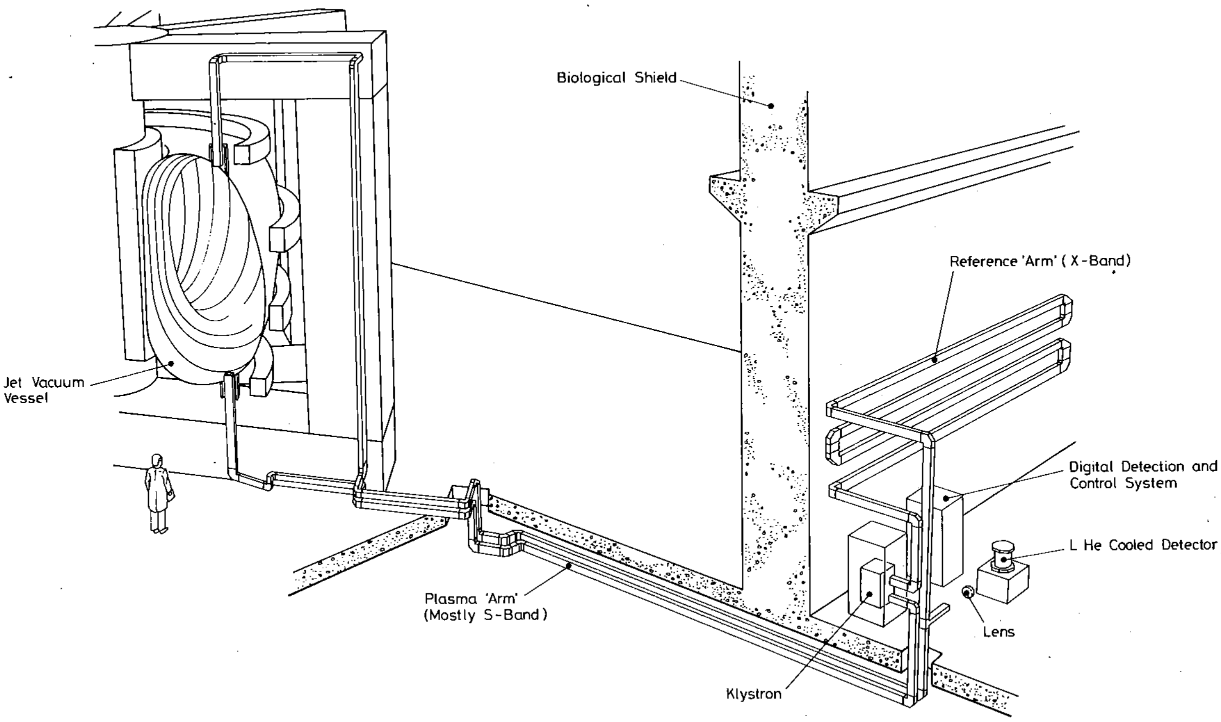

Fig. 1 Schematic of JET 2mm microwave interferometer

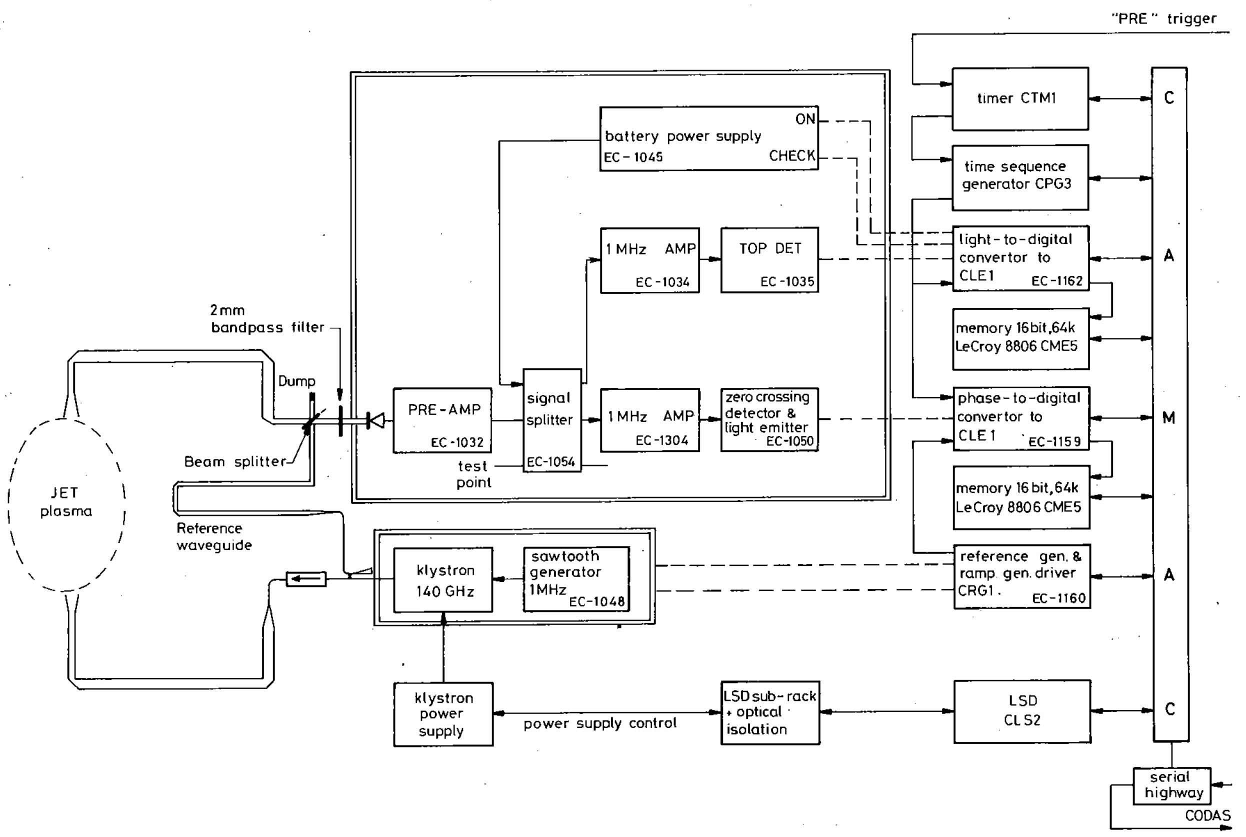

Fig. 2 Interferometer block diagram.

System Description

The interferometer is of the Mach-Zehnder configuration using a swept frequency klystron and unequal length plasma and reference arms (Figures 1 and 2) [2]. In the absence of plasma the frequency excursion is adjusted to produce a phase change of $0 \rightarrow 2\pi$ between the reference and plasma arms for each cycle of a sawtooth modulation voltage. The required frequency excursion, Δf, is given by $\Delta f = c/\Delta L$ where c is the velocity of light and ΔL is the path length difference. ΔL is typically a few metres. The chosen intermediate frequency of the sawtooth modulator is 1 MHz. The detector is followed by a narrow band (100kHz) amplifier centred on 1 MHz to filter out the flyback of the sawtooth waveform and to reduce detection noise. The resultant 1 MHz sinewave output is then compared with the reference 1 MHz signal. The electron density evolution is determined by measuring the accumulated phase difference, $\Delta\phi$, between these two signals.

The system uses a conventional Varian klystron source, a PSU/control unit developed by Culham Laboratory and a fast InSb liquid helium cooled detector from QMC Instruments (estimated NEP of 2×10^{-12} W/Hz$^{1/2}$). Post detection electronics were developed by FOM Instituut voor Plasmafysica. [3].

The Waveguide Configuration

It is normal practice to use oversized waveguide to avoid the untenable attenuation of fundamental waveguide at millimetre wavelengths. The attenuation of the fundamental mode in very oversized waveguide ($\lambda \ll$ a or b where a and b are the dimensions of the waveguide) is inversely proportional to the length of the waveguide wall parallel to the electric vector. Pure aluminium WG 10 guide has been used in the interferometer with the electric vector parallel to the longer wall. The measured attenuation at 2.2mm was < 0.06dB/m which was acceptably close to the calculated value of 0.04dB/m.

For low mode conversion losses and compactness in such an oversized system, mitre bends must be used. The theoretical loss for a perfect bend of this type is $1.96\,(\lambda/b\sin\theta)^{1/2}$ dB for an E-plane and $2.05\,(\lambda/a\sin\theta)^{3/2}$ dB for an H-plane bend where θ is the angle of the bend. The minimum attenuation for 90° bends is 0.33dB and 0.03dB respectively. (Wavelength = 2.2mm, a = 34, b = 72mm). In addition any tilt between the axis of the guide and the connecting flange face will give rise to serious losses as shown in Figure 3. Thus, for a low attenuation oversized waveguide system the total number of bends should be minimised, H-plane bends should be used in preference to E-plane bends and the manufacturing and installation tolerance should ideally be better than 0.1 deg. [4].

In the JET configuration these criteria have been followed where possible but the routing of the waveguide between the diagnostic apparatus and the Torus has necessitated the use of 24 of the specially developed mitre bends and about 70m of waveguide. The total attenuation including the Torus gap loss was measured to be 65 ± 3dB.

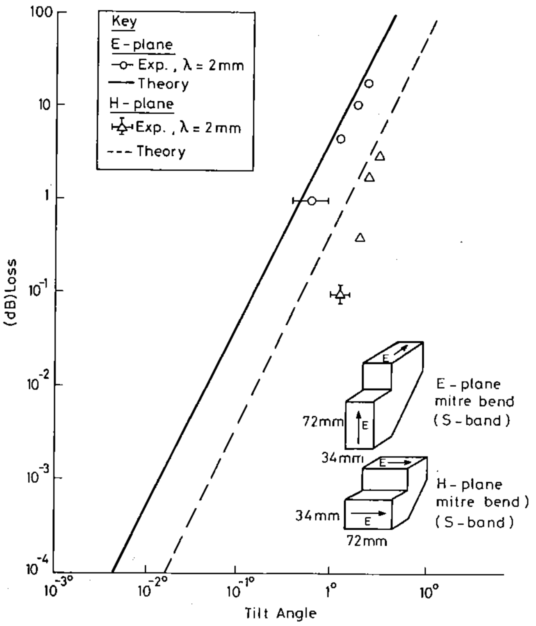

Fig. 3 The effect of waveguide misalignment.

Detection Electronics

Figure 2 includes a block diagram of the detection electronics. Three special CAMAC-units were developed for this interferometer by FOM. These were

(a) A ramp control/reference generator module to both (i) control the 1 MHz sawtooth generator which modulates the klystron frequency and (ii) generate a reference 100MHz pulse signal for the phase to digital convertor. The sawtooth generator itself is powered from the klystron filament supply and is floating on the klystron beam supply voltage. Fibre optic coupling is used between the CAMAC module and the sawtooth generator.

(b) A CAMAC unit with fibre optic input to read the amplitude of the detected interference signal. This signal is used to check the interferometer performance during a plasma pulse. The results are stored in a 16 bit 64K LeCroy memory.

(c) A phase-to-digital converter module which digitises the phase-shift between a 1 MHz reference signal and the amplified ~ 1 MHz detector signal. The unit measures the change in phase-shift between sample pulses and writes it as a 16 bit word into a second 64K LeCroy memory. The format of the 16 bit word is as follows: the 8 LSB's contain the fraction of a fringe with a 3.6° accuracy. The next 7 bits contain the number of whole fringes and the MSB is a warning or error bit which is set when the rate of change in phase-shift exceeds a pre-settable value. The counter frequency of the phase-to-digital convertor is 100MHz. The final density trace is formed by software integration of the phase shift samples.

Results

Virtually all JET plasma density measurements, up to the present time, have been made using the 2mm system.

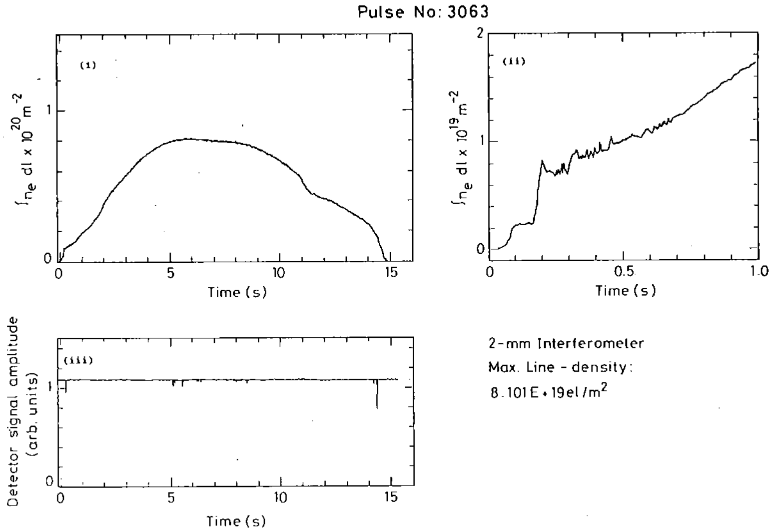

Fig. 4a (i) Evolution of the line of sight density integral for a JET pulse.
(ii) Blow up of the first second of (i).
(iii) Detector signal amplitude during pulse.

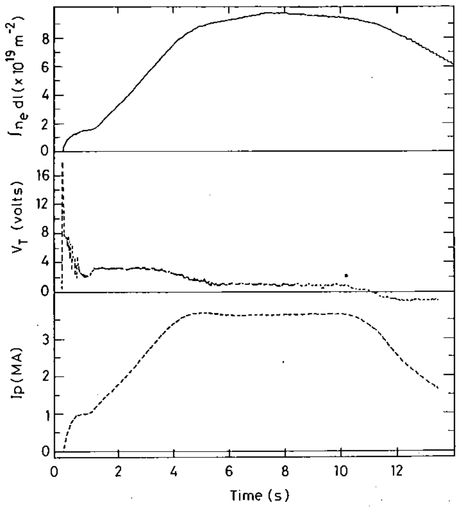

Fig. 4(b) Upper — line of sight density integral
Centre — Toroidal voltage
Lower — Plasma current

Figure 4a shows an example of the electron density and signal amplitude waveforms taken from a recent JET pulse. Figure 4b shows the density signal compared with current and voltage waveforms. A comparison of preliminary data from the JET FIR interferometer with that from the microwave instrument shows agreement to within ~ 3% during the pulse flat top period.

The detection noise limit of the system corresponds to about ±20 millifringes whereas at maximum density the plasma pulse shown produced ~ 100 fringes. Thus the resolution of the instrument at the density maximum is 1 part in 5000. The value of this high resolution is illustrated in Fig. 5. Sawteeth oscillations corresponding to ~ 1% variation in the $\int n_e d\ell$ amplitude, are easily resolved in the expanded waveform Fig. 5b. Fast oscillations on the individual sawteeth of only 0.1% of the amplitude are also resolvable when the data is further expanded. In the example shown in Fig. 5c, these faster

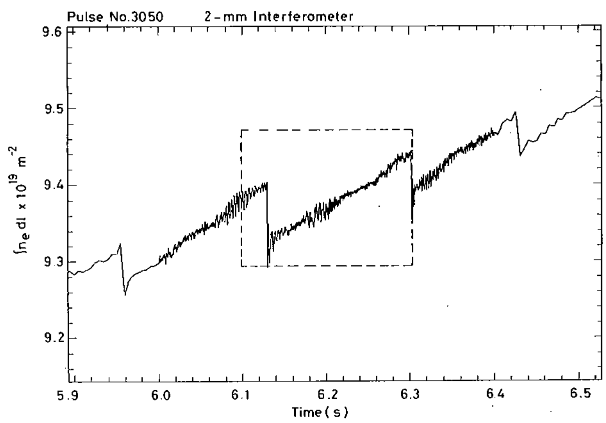

Fig. 5(b) Expanded waveform showing sawtooth oscillations.

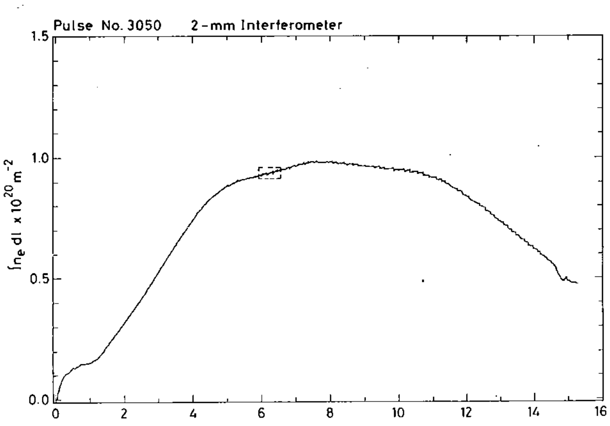

Fig. 5(a) Density waveform indicating expanded region.

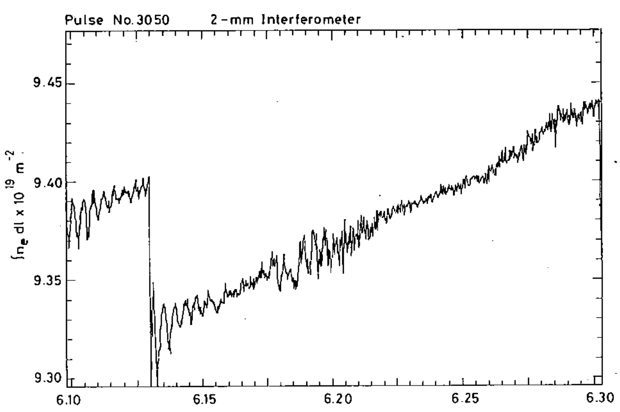

Fig. 5(c) Further expansion showing high frequency fluctuations on the sawteeth.

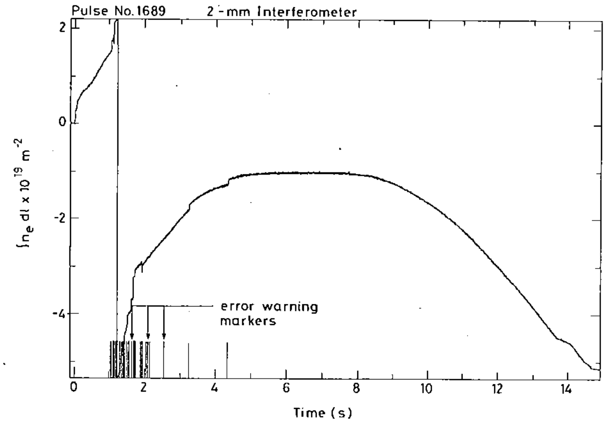

Fig. 6(a) Corrupted density waveform caused by minor disruptions during plasma current rise.

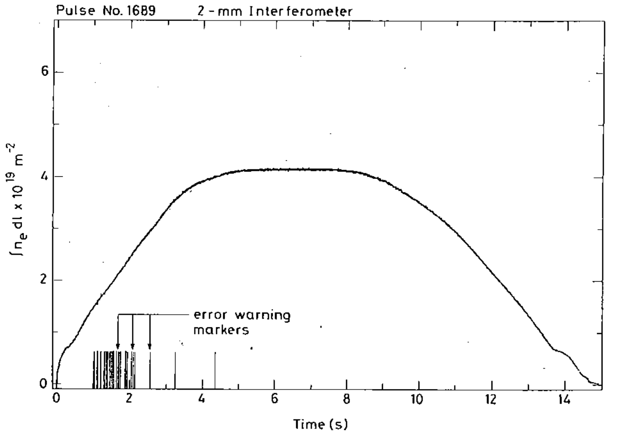

Fig. 6(b) Waveform after processing with automatic reconstruction program.

oscillations can be observed when the instrument's fast sampling (5kHz) period was switched on between 6.0 and 6.4 sec. for this pulse.

As with many such interferometers, rapid changes in density associated with minor and major disruptions of the plasma can cause phase sampling errors. However, when this occurs with our instrument, because the errors or error warnings are all flagged by the hardware, it is possible in many cases to re-analyse the data off line and try to re-construct the corrupted waveform. This has been done by indentifying and correcting the faulty samples either manually or with an automatic correction program. For the results shown in Fig. 6a the error warning bit was set wherever the phase shift between 1 μsec samples exceeded 36°. All samples with error warnings are indicated on the Figure 6a by a 1/10 full scale vertical bar, marking the times at which phase measuring errors may have occurred. The result of using the automatic reconstruction program is shown in Fig. 6b.

For minor disruptions, provided the incidence of error flags is not high the technique appears to work well, returning the phase signal to zero at the end of the pulse. Major disruptions, however, create a very high incidence of errors from which it has not been possible as yet to recover the complete density history. Normally the data is reliable until such an event occurs on the waveform, i.e. until the onset of a major disruption.

Conclusion

A simple 2mm microwave interferometer has been constructed primarily for electron density measurements during the ohmic phase of the JET Tokamak programme. The system features a long oversized waveguide run with many bends, to enable operation with all the active components outside the JET biological shield. The integrated line of sight electron density can be measured to better than 3% accuracy at peak density.

The choice of the relatively long wavelength provides the instrument with intrinsically high density resolution. Fluctuations of 0.1% of the peak of the line integrated density can be observed and the potential for studying MHD oscillations is clearly demonstrated.

Acknowledgements

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